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DATA PROCESSING BY MEANS OF FUNCTIONAL OPTRONS

by

K.F. Bierkowskaja, J.P. Biernsztejn, et al

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DATA PROCESSING BY MEANS OF FUNCTIONAL OPTRONS*

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S.B. Gurewicz, B.G. Podlaskin

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The present tendency for ever increasing amount of data which has to be processed at high speed has created the problem of a preliminary processing of analyzed images. Among operations connected with imaging, which shorten considerably the time used by computers in further processing, one should mention: formation of characteristics which remain unchangeable with respect to any group of transformation, standardization, codeing, calculation of correlation measures between models and recognized images, looking for a known fragment against unknown background, associative selection according to contents, etc.

The search for technical means which would enable effective performance of these operations connected with imaging is now being done in many studies both in the area of the design of analog optical processors working in coherent and incoherent light /1 - 3/, and in the area of the design of specialized microelectronic structures /4 - 7/.

The aim of this study is an analysis of the possibility

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*An article translated from Mikroelektronika, vol. 6, No. 3, 1977 (USSR) of making a semiconductor device, integrating the function of a photodetector mosaic with certain functions of a space modulator with controlled transmittance (transparency), i.e., being in fact an analog optoelectronic processor.

Let us consider technical possibilities of performing a universal integrating operation of the type:

$$a_{nm}[f] = \iint\limits_{L_x L_y} f(x, y)\, S_{nm}(x, y)\, dx\, dy \qquad (1)$$

in which:

$f(x,y) = \{f^{kl}\}$ - examined multivalued optical signal,

$S_{nm}(x,y) = \{S^{kl}_{nm}\}$ - analysis function with number nm, $n = 1,2 \ldots N$, $m = 1,2 \ldots M$, $k = 1,2 \ldots K$, $l = 1,2 \ldots L$,

$a_{nm}[f]$ - functional of number nm, characterizing the examined function $f(x,y)$,

L_x, L_y - integration area.

The aim of calculations is subordinating the examined function $f(x,y)$ to the matrix of the values of coefficients $\{a_{nm}\}$ which, depending on the choice of the analysis function $\{S_{nm}(x,y)\}$, will correspond to coefficients of Fourier series, values of the functions of merging, correlation, autocorelation, or certain arbitrary primary characteristics, on the basis of which one can effect recognition of the picture (image) /8, 9/.

In the first two cases mentioned previously the examined function itself and each of the NM analysis functions must be represented with MN selections in such a way that the number of selections equals the number of the analysis functions.

In the third case - formation of preliminary characteristics, the number of analysis functions NM may be smaller than the number of selections of the function KL.

Let us compare two technical forms of processors - analog optical processors (AOP) and specialized microprocessors (SM) - performing one and the same transformation:

$$\{f^{kl}\} <==> \{a_{nm}\} \tag{2}$$

in which a_{nm} is calculated according to (1), and the collection of all the analysis functions, the matrix with NMKL elements, is in the memory of either of the two types of processor.

If introduction of NM analysis functions is realized by the method of element after element - in series, then calculation of the matrix $\{a_{nm}\}$ requires NMKL logical steps. (As a logical step one considers the performance of one "basic" operation - combined complex multiplication plus combined addition). Moreover, the value of the total time of processing should include also the time required to introduce the examined picture. If this introduction is done by means of a scanning converter of television type, i.e. on one channel, then we require still more "KL" steps. In this way, when applying the series-series introduction of the examined function and the analysis function, the number of steps $\bar{\theta}$ will be

$$\theta = KL(NM+1) \tag{3}$$

We have to note that the FFT algorithm /10, 11/, which decreases considerably the number of calculation steps, is applicable only to specific analysis functions (expansion into series of Fourier or Walsh functions). It requires also a certain time for introduction of the examined functions and a considerable capacity of memory for these entries.

In contrast to such "series" methods, already at the beginning of the sixties the attention of investigators began to be concentrated on developing specialized calculation systems in which the ratio of series operations to parallel operations changes in favor of the parallel ones, and the logical depth of calculations, i.e. the number of logical steps, decreases. In such systems of analysis, the reproduction through a suitable parallelism of the calculation process tends to achieve the "full" solution, with regard to the number of elements. Correspondingly, the logical step contains in itself simultaneous execution of the operation for the whole matrix of numbers. Systems of this type are realized both by optical methods and methods of microelectronics, in the form of uniform, repeated structures.

Analog optical processor (AOP)

At the beginning let us recall how the processing (conversion) /1/ is realized by means of analog optical methods.

The examined signal $f(x,y)$ is introduced into an analyzer through a spatial modulator of a coherent light stream. The analysis functions $[S_{nm}(x,y)]$ are introduced into the analyzer in the form of transparencies with modulated clearness (opaqueness), located at a certain plane (level), onto which the picture of the examined signal $f(x,y)$ is projected by means of an optical system. The stream of light collected by optical system in the new plane has in its cross-section a space modulation of the type

$$f(x,y)\, s_{nm}(x,y) = q_{nm}(x,y) \tag{4}$$

If a photoelement integrating the light beam is placed in this plane, the resultant values of photoelectric current J_{nm} are proportional to values of the functional "a_{nm}" with coefficient a :

$$J_{nm} = a \int_{L_x}\int_{L_y} q_{nm}(x,y)\, dx\, dy = a a_{nm} \tag{5}$$

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The matrix of value $\{a_{nm}\}$ can be obtained after NM cycles , as also after one cycle. In the first case, to each cycle corresponds the change of reproduction of analysis function (see Figure 1, which for clarity shows also the mechanical change of the transparency). In the second case, the whole set of analysis functions $\{S_{mn}^{kl}\}$ is synthesized simultaneously on one transparency, and reproduction of the examined function is repeated. In this way, parallel processing of reproduction in NM channels is carried out (see Figure 2). Hence, for AOP with series-parallel entry $\{S_{mn}^{kl}\}$ the required number of logical steps is

$$\Theta^{AOP}_{\substack{series\\paralel}} = NM \tag{6}$$

For AOP with parallel-parallel entry $\{S_{mn}^{kl}\}$ the required number of logical steps is

$$\Theta^{AOP}_{parallel} = 1 \tag{7}$$

The synthesis of analysis functions in the form of optical mask-transparencies and organization of their selection in time (Figure 1) and in space (Figure 2) necessitates overcoming some real technical difficulties.

We shall note that narrowing of the class of analysis functions to the family of combined exponential functions $\{\exp(j\omega t)\}$ allows to simplify process of the synthesis of mask--transparencies, and to find simple and "natural" methods of modulation of the light stream, both in the variant of dynamic selection of masks /12, 13/and in the multichannel parallel-parallel variant (lens /3/). In these cases, difficulties of the synthesis of transparencies are merely transferred to the process of the precision making of optical details.

In this way, in comparison with the direct method /3/, AOP enables to reduce considerably the number of logical steps, for instance see (6), (7). This shortening of the time of processing is achieved at the cost of utilization of determined optical connections in the optical system, i.e., connection of "processor" and "memory block" containing information about the analysis functions $\left\{ S_{nm}^{kl} \right\}$, and at the cost of application of the analog operation of summation at the outlet of device.

The accuracy of calculations and the dynamic range of the processor are limited by the accuracy of carrying out the mentioned analog operation, by fluctuations of the intensity of the light stream, the accuracy and dynamic range of transparencies and by the outlet analog-digital converter.

The basic difficulty in realization of AOP, as well as an obstacle for the mass application in the character of microprocessor, is the lack of satisfactory transparencies with controlled transmittance and of the multiplicators of reproductions (images).

Specialized microprocessors (SM)

It can be assumed that the functional relatives of AOP are such specialized microprocessors in which introduction of the analysis function $\left\{ S_{nm}^{kl} \right\}$ is realized not at the cost of the change of reflection or transmittance of light, but at the cost of carrying out logical operations on photocurrent in each elementary cell.

As an example we can mention various iterative systems /14/ including a "sequential" filter /15/, associative systems of memory on bipolar elements and MIS /16, 17/, etc., where various analysis functions are synthesized in the form of value masks, i.e.

$$S^{kl}_{nm} = \begin{cases} \\ 1 \end{cases}$$

The basic difficulty in realization of SM is to connect the mosaic of photodetectors with logical elements, while satisfying the requirement of maintaining a high coefficient of utilization of photosensitive surface. This problem could be solved through construction of multilayer LSI instruments. The modern methods of photolitography have solved only the problem of interelement connections on the plane, but not in the volume, since soldered junctions for each element, "beam" protrusions, glass-metallic and other outlets, etc., cannot secure the required simplicity and reliability of functioning of the device /18/. Solution of this problem by means of integrated optics /19/, or on the basis of hybrid multilayered optico-electric systems /20/, which are still at the planning stage, should be considered as AOP. Indeed, there is no sense to limit ourselves in application of such rather complicated active systems merely to passive "distribution" of light beams - since along with "distribution" there will be realized also the interelement control through the light beams. Let us assume that the examined **signal** $\{f^{kl}\}$ is being introduced into SM through the spatial modulator of light beam, which distributes itself optically, for instance by means of fiber optics, to elementary cells containing photoreceiving elements.

At first, let us stop for a while to consider a "simple" series-series electrical method of synthesis of analysis function $\{S_{nm}^{kl}\}$ by means of logical elements of matrix. The control of elements is effected according to the system of mutually-perpendicular rails. Then, for calculations of the whole matrix $\{a_{nm}\}$ the required number of logical steps is given by the equation:

$$\Theta^{SM}_{\substack{\text{consec.}\\ \text{series}}} = NMKL \qquad (8)$$

Parallel optical introduction of one function of analysis should be effected with simultaneous projecting of the whole "page" of data on analyzing matrix, for instance from optical memory device /21/. The choice of the analysis function is done according to series selection of "pages". 201

Simultaneous electronic introduction of any arbitrary analysis function in the system of mutually-perpendicular rails is impossible, because of the internal electrical coupling in the matrix. However, by limiting the class of synthesized function and by enlarging somewhat the logical part of each elementary cell, it is possible to synthesize one analysis function in one cycle of operation of the arrangement /15/.

$$\Theta^{SM}_{\substack{Series \\ Series}} = NM \tag{9}$$

A microelectronic arrangement corresponding to AOP with parallel--parallel introduction of $\{S^{kl}_{nm}\}$ (Figure 2) foresees branching of KL signals along the NM channels. Electrical "distribution" of signals is not practical because of the lack of multilayer LST systems. If, as previously, we apply optical multiplication of reproductions (images) then the parallel synthesis $\{S^{kl}_{nm}\}$ can be realized on NM matrices with KL elements in each, or in the form of permanent memory (for instance, appropriate photoreceiving cells are not connected to rails) or also in the form of semi-permanent memory. In the last case, one makes first "preparation" of the logical part of the elements of the matrix in the system of mutually perpendicular rails, by the method of element after element, in series. Then, not considering the time for "preparation"

$$\Theta^{SM}_{parallel} = 1 \tag{10}$$

In principle, such a system is very close to the analogous AOP system. It still contains difficulties with multiplication of images, and difficulties connected with making of transparency with the image $\{S^{kl}_{nm}\}$ are now changed to difficulties with its "printing" to a large photosensitive matrix containing NMKL elements. An advantage of the SM system is the lowering of requirements with respect to the dynamic range of photoelements. In this way, the reduction of processing time achieved in SM (compare /3/, /9/ and /10/) is due to the parallel introduction of analysis functions to the matrix of the analyzer by optical or electronic method, and to utilization of the analog operation of summation at the outlet of the arrangement (although in each elementary cell the operations need not be of analog type).

The accuracy of such a computer depends, first of all, on the number of used elementary cells (KL), uniformity of photoelements and their dynamic ranges, and quality of the output analog-digital converter.

Scanistor optoelectronic processor (SOP)

We have proposed /22/ that a new promising technical method of obtaining a computer performing functional processing (1) is to make a photodetector mosaic with controlled photosensitive surface.

Let us assume that the spatial distribution of intensities of the beam of light is represented by a matrix of value $\{f^{kl}\}$ and that internal photovoltaic effect converts it into matrix of the value of photocurrents $\{i^{kl}\}$.

The most often used method of controlling elements of photosensitive matrices, with the series - element after element selection, is the system of mutually perpendicular rails /23/.

In this system of control, in one working cycle we can prepare for photodetection areas corresponding to whole columns and rows or one element chosen at will. The analysis functions of any configuration can be introduced into the arrangement only in NMKL cycles through the series synthesis of function $\{S_{nm}^{kl}\}$ (8). We put before us the goal to develop such a structure of a matrix and its elements which, with restriction to series-parallel control, would broaden the class of analysis functions synthesized in one working cycle of the arrangement.

We shall explain how one can build a processor realizing the operation (1) with the use of profile functions in the character of analysis functions. We shall use here a known commutational photoelement - multiverse scanistor /24/, which is characterized by a high coefficient of filling the surface by photosensitive elements (about 90%).

Figure 3 shows a semiconductor p-n-p structure. The analyzed image is projected onto the front surface of monocrystal 1 of the n type. This surface has strips 2 of the p type and numbering M. A semi-insulating surface 3 of the base type ensures electrical separation of elementary areas /25/. The back surface has a mutual layer 4 of the p type with leads 5. It fulfills the function of a divider of the steady polarization potential 6.

As distinct from the traditional scheme of connecting the scanistor with common generator of commutating signal, in the system of synthesis of analysis functions each row is controlled from independent source 7. Let us assume that the p-n junctions were formed at such a distance from surface, that free pairs of carriers generated by photons reach only the p-n junction at the front surface. Let us assume further that photocurrents are considerably larger than the dark current of barrier polarized p-n junctions (Figure 4a), i.e., we have

$$i_f = i \gg i_s$$

Then, at each moment of time t for any m-th verse, the source of polarizing potential 4 and generators of variable potential 7 cause levels OV, forming equipotential lines whose locations define transitory values of commutating potentials. On one side of the equipotential the current is negligibly small, and on the other side - with coefficient a - proportional to the potential of beam along the row $f^m(x)$. Then the total current from the whole structure in the summator 9 will be

$$J = \sum_m i^m = \sum \int_0^{x_0^m(t)} a f^m(x)\, dx \qquad (11)$$

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If the number of allowable locations is N, then (10) is equivalent to (1), provided we utilize profile functions in the character $S_{nm}(x, y)$, that is

$$S_{nm} = \begin{cases} 1 & x, y \in S_{nm}^{(1)}, \\ 0 & x, y \in S_{nm}^{(2)}. \end{cases}$$

$S_{nm}^{(1)}$ and $S_{nm}^{(2)}$ are two areas limited by dimensions of the surface of photoelement and by location of the equipotential at **zero level. Let** us recall that in the traditional scheme of the commutation of scanistor in after-channel differentiating arrangements, the currents i^m are converted into potentials of the videosignal U_b^m, that is

$$U_b^m = B\frac{di}{dt} = Bf(x_0)\frac{dx_0}{dt},$$

at which

$$B\frac{dx}{dt} = B' = \text{const.}, \quad U_b^m = B'f^m(x),$$

for series commutation of rows. This is equivalent to the series selection according to register. In the system of synthesis of profile functions, full current is registered through structure (11).

Let us assume that the potential at the outlets of generators 7 changes step-wise at intervals T_s. Then, to each application of potential on the rows of scanistor at time intervals $T_s = T_{nm}$ (Figure 4b) corresponds its own function:

$$J(t) = J(T_{nm}) = \alpha a_{nm}[f], \quad n = 1, 2, \ldots N, \quad m = 1, 2 \ldots M.$$

In this way, a multirow scanistor with potential-current characteristics nonsymmetric with respect to light (load carriers generated by light are distributed only in the p-n junction from the front side) with divider element in each cell may be applied in the character of image analyzer, combining the functions of an integrated photodetector and a synthesizer of mask-transparencies in the form of profile functions. The class of synthesized mask-transparencies may be broadened to functions with separable variables $S_{nm}(x,y) = S_n(x) \cdot S_m(y)$ /26/ after certain constructional changes of the receiver matrix. Figure 5 shows a matrix of photodetectors whose elements, similarly as before, are formed by the p-n-p structure. The location of the p-n-p structure corresponds to the area of the crossing of strips of the type p, formed on the front 1 and rear 2 surface. The volume between strips of type p is filled up with monocrystal of type n 3. In difference to the design discussed previously, one obtains here symmetrical potential-current characteristics (Figure 6a) through the proper choice of the distance of junctions from the front and rear surface, and the choice of wavelength of light acting upon the arrangement. Therefore, we have

$$i_f^{(1)} = i_f^{(2)} = i_f > i_s .$$

Zones $S^{(2)}_{nm} = 0$ arise as a result of imposing zero polarization onto the crossing of rails corresponding to the given elementary cell. Zones $S^{(1+)}_{nm} = +1$ and $S^{(1-)}_{nm} = -1$ are formed as a result of positive or negative polarization at the crossings (Figure 6b), while photocurrents in block 6 are summed up with respect to their absolute values. In this way, a modification of multirow scanistor with symmetrical potential-current characteristics and a system of columns from the rear side may be applied in the character of an imaging analyzer. This analyzer combines the function of an integrated photodetector with the function of a synthesizer of mask-transparencies with separable variables, including systems of fully orthogonal functions (for instance Walsh functions, Figure 6c). We shall note that multirow scanistors may be applied in the character of multioutlet generators of the control potentials /27/. Program of the change of masks is introduced into them optically, and then the whole processor is constructed from identical elements.

In principle, it is technologically possible to form in the only p-n-p elementary cell not only functions of photoelement and control of transparency, but also an element of emitting matrix /28/ (one of p-n junctions emits at a determined polarization and illumination of another p-n junction). Then the result of multiplication of the examined function and synthesis function will be as follows:

$$q_{nm}(x,y) = f(x,y)\,S_{nm}(x,y),$$

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and may be represented in the form of a new emitting configuration $\{q_{nm}^{kl}\}$ controlling the entry of the next layer of the converter /29, 30/.

In this way, SOP solves the problem of design principles of SM for a number of specialized analysis functions.

Indeed, the problem has been solved of connecting the photoelectric and logical parts of elementary cell in the simplest p-n-p (n-p-n) structure, while the coefficient of utilization of photosensitive surface is sufficiently high to be able to analyze imaging in the "natural" form - without previous optical "distribution" to elementary cells.

Final conclusions

Up to this time, considerable number of optical and optoelectronic processors, both for sufficiently broad application and for narrow specialized purposes, have been proposed and in many cases already accomplished. They show a variety of technical solutions, including matrices of holograms, hybrid controlled transparencies, elements of integral and volume optics, complex mechanical modulators of LSI systems, connected with the matrix of photodetectors, etc. This variety makes it difficult to make comparisons. Such important indicators as accuracy of calculations and time required to perform a logical step are determined by the actual phase of constructional development of a given device, hence comparison of processors which are at different development stages is difficult. However, the threshold, limiting possibilities for all these varied arrangements, irrespective of whether they are utilizing the coherent or incoherent light, are limited by the same basic reasons connected with quantum properties of radiation and the molecular, atomic or electron features of effects in modulating and registering centers.

We shall compare these arrangements on an example of performing one concrete operation - generalized spectral analysis, and according to one indicator - the number of logical steps necessary for calculating the matrix of functionals.

The comparison shows (3), (6) - (10), that the design principle of the processor, the degree of simultaneity of performing operations, the level of connection of the processor with memory containing information on the matrix $\{S^{kl}_{nm}\}$ from NMKL elements, determine the general number of logical steps required for carrying out calculations. In the case of large matrices, this value decides about the speed of the system as a whole, irrespective of the time of realization of one logical step.

The "fastest" syntheses with parallel-parallel introduction of the analysis function are obtained when the memory containing all analysis functions is practically fully connected with its own processor (Figure 2). Systems with the series-parallel selection of analysis functions are "slower", but they are technically simpler, particularly in those cases when not any optional analysis function but only a specialized function is introduced. The memory is then only partially connected with the processor, and partially with the external control blocks (Figure 1).

A variant of such a design of computer is the scanistor optoelectrical computer type SOP.

A processor in the form of SOP enables to solve a relatively broad circle of problems connected with automatic recognition and classification of images. The task of introducing the image into automatic devices for recognition cannot be considered per se as a solution. The known semiconductor mosaic devices with photodiodes of the type p-i-n , matrix on transistors MIS and CTD structure are very complicated and too expensive for application on a broad scale in lines of automatic control of production processes. Moreover, introduction of imaging according to the series -(element after element) method requires a large capacity of memory and a complicated system of the logical conversion of the videosignal. Therefore, we recommend for introduction of images to automata not to use simple devices corresponding to vacuum television tubes, but photo-elements which can accomplish, in addition to registration of the distribution of potentials of the beam, also functions of some preliminary logical transformation of images. Introduction of imagesis realized in this case in the form of introduction of the values of functionals $\left[\alpha_{nm} \right]$, while the system of analysis functions $\left\{ S_{nm}^{kl} \right\}$ is chosen each time in such a way that for given identified images the division into previously discussed classes is effected with participation of the least number of functionals. Such a matrix, combining the functions of photodetection and spatial modulation - masking (although with only a limited class of synthesizing functions) is simpler in technological construction and is more reliable than the mentioned devices with mosaics. Moreover, it is characterized by entirely satisfactory parameters in the areas of selectivity and speed of action /24, 26/.

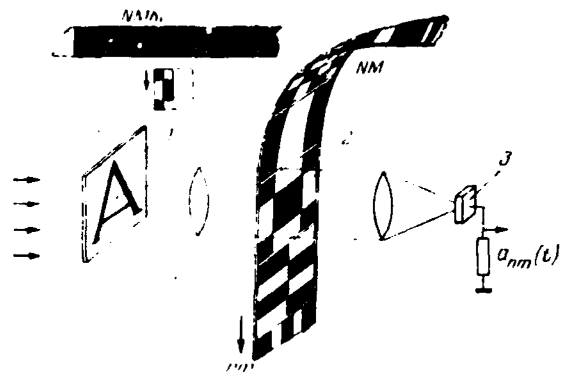

Figure 1. Block diagram of a one-channel optoelectronic processor with the series-parallel synthesis of analysis function (at the left top corner is an example of the series-series synthesis of analysis function): 1 - plane of synthesis of analyzed picture, 2 - plane of synthesis of analysis function, 3 - integrating photoreceiver

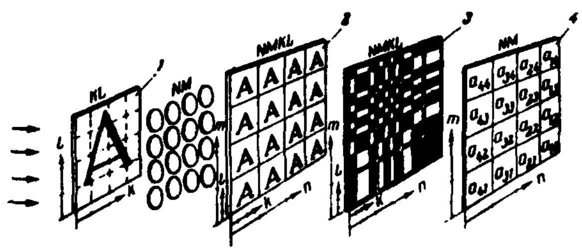

Figure 2. Block diagram of a multichannel processor with the parallel-parallel synthesis of analysis function: 1 - plane of synthesis of analyzed picture, 2 - plane of synthesis of multiplied analyzed picture, 3 - plane of synthesis of analysis function, 4 - plane of synthesis of the values of functionals

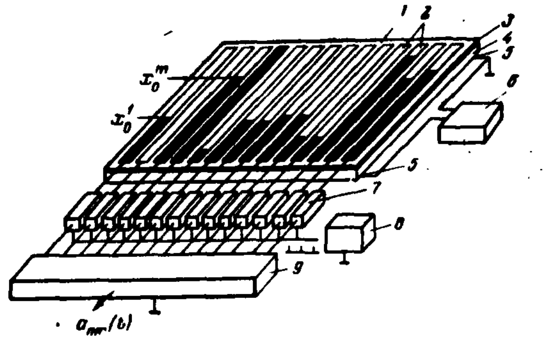

Figure 3. Connection diagram of an optoelectric processor of scanistor type ensuring the synthesis of profile masks: 1 - front plane of n(p) monocrystal, 2 - photosensitive p(n) verses, 3 - n(p) mutual area of base type, 4 - p(n) rear plane (divider), 5 - connections to divider, 6 - source of polarizing potential, 7 - generators of variable potentials ensuring the order of synthesis of profile masks, 8 - generator controlling the frequency of the change of masks, 9 - summator

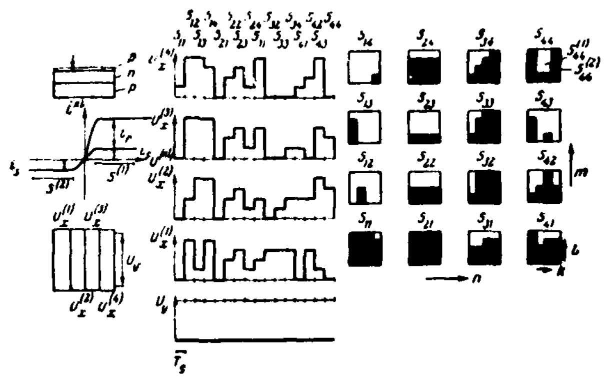

Figure 4. Dynamics of the formation of masks on photoreceiving matrix in Figure 3: a) potential-current characteristics of illuminated nonsymmetrical p-n-p (n-p-n) structure and markers of time intervals; b) graphs of potentials exciting the verses and bringing potentials to the divider; c) the corresponding profile masks of photosensitivity synthesized in the receiver panel

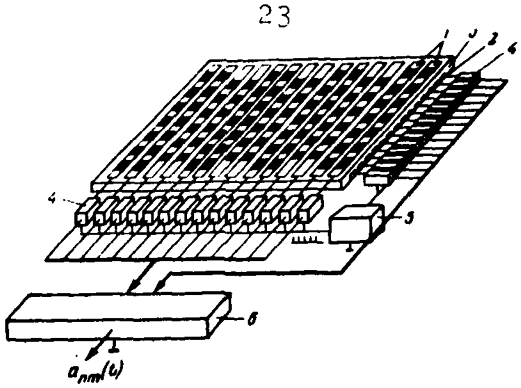

Figure 5. Connection diagram of an optoelectronic processor ensuring the synthesis of twodimensional masks with separable variables x and y : 1 - photosensitive p(n) strips at the front surface, 2 - p(n) strips at the rear surface, 3 - common area n(p), 4 - generators of potentials enabling the synthesis of masks, 5 - generator controlling frequencies of the change of masks, 6 - summator

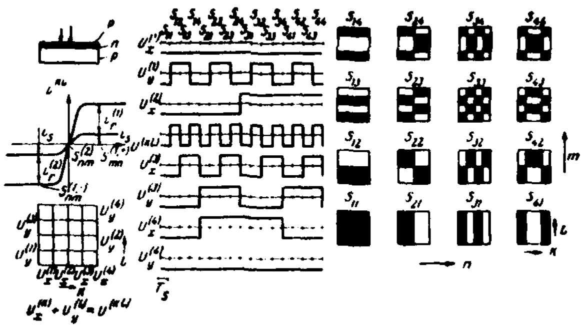

Figure 6. Dynamics of the formation of masks on photoreceiving matrix in Figure 5: a) potential-current characteristics of symmetrical p-n-p (n-p-n) structure and markers of rails; b) graphs of potentials on mutually-perpendicular system of rails; c) the corresponding masks of photosensitivity synthesized in the receiver panel

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